Sādhanā (2020) 45:237
https://doi.org/10.1007/s12046-020-01476-1

An application of evaporation-rate-based water cycle algorithm for coordination of over-current relays in microgrid

SAGAR KUDKELWAR and DIPU SARKAR*

Electrical and Electronics Engineering Department, National Institute of Technology, Dimapur, Nagaland 797193, India
e-mail: sagarkudkelwar100188@gmail.com; dipusarkar5@rediffmail.com

MS received 2 May 2020; accepted 5 July 2020

Abstract. Relay coordination is reliable and crucial to guarantee that healthy feeders are properly isolated from the defective areas in a microgrid network. An appropriate protection scheme must be properly planned during the design of the microgrid to ensure safety for the power components in the event of a failure. The implementation of distributed generators in the microgrid changes the total network's Load-Flow and often impacts the magnitude and direction of the fault current. Using the nature-inspired novel evaporation-rate-based water cycle algorithm (ERWCA), the enhancement in microgrid protection is accomplished in this work by optimizing the relay settings, reducing their operation time and time dial setting of each relay. The approach proposed is validated with the IEC microgrid benchmark system and the findings are contrasted with current techniques. It is found that the proposed strategy produces substantial improvement for the microgrid in the application of over-current relays and greatly reduces the relays' overall net operating time.

Keywords. Time dial setting; microgrid; evaporation rate water cycle algorithm.

1. Introduction

Relay protection is an integral part of the power grid service. Relay coordination is an essential component in the design of protection systems, as relay coordination schemes must ensure quick, effective and selective operation to isolate the defective segment of the network. The technical and economical alternative for the protection of the integrated sub-transmission and distribution network is directional over-current relays (OCRs). Due to the introduction of distributed generators (DGs) and the growing development in smart grids, distribution networks are increasingly evolving from traditional radial design into loop or mesh structure [1].

In particular the implementation of DG substantially impacts distribution networks, and their effect on the protection system is one of the key concerns. The type of DG and complexity of distribution network decides the impact of DG penetration in the protective scheme. High fault current generated by synchronous-based DG (SBDG) as contrasted with inverter-based DG (IBDG) has been seen in [2], resulting in a much deeper impact on protection systems. Typically, protection schemes for the radial distribution network are provided by fuses, re-closers and OCRs. Coordination of protection for such devices has almost zero impacts for IBDG. However, on the contrary, when SBDG is present in the network, fuse will first work before re-closure behaviour, leading to fuse saving approach. Additionally, SBDG may have an effect on fuse-to-current relay coordination leading in an unexpected trip on the entire feeder. Either fuse replacement or correct tuning of re-closer setting or OCR setting would be required to alleviate these problems [3].

For meshed type distribution systems, DG can continue to feed up the power through other feeders even after fault isolation. Therefore, for meshed type DG integration system only directional OCR is a unique option due to its bidirectional fault current handling nature because these relays can be optimally coordinated to reduce the overall operating time of a protective scheme through its Time Dial Setting (TDS) [4]. OCR is integrated with two settings, i.e. Time Dial Setting (TDS) and Plug Setting (PS). Therefore, relay coordination is an optimization problem and can be solved using mathematical optimization methods and metaheuristic techniques. In the early days, the researcher had suggested linear program (LP) methods such as simplex, dual simplex and two-phase simplex methods [5–7]. In LP, the value of PSs needs to be fixed and TDS has to be optimized. However, some researchers commented on the weak performance of LP and proposed the Non-Liner Program (NLP) to optimize both TDS and PS. The applied NLPs on relay coordination problems are Interval LP, constrained quadratic programming and SQP, etc. [8–10]. Since the last decades, heuristic approaches had been suggested for more optimization and quicker solutions. GA, particle swarm optimization (PSO), ACO and DE are the

*For correspondence
Published online: 11 September 2020

most famous techniques utilized for relay coordination purpose [11–14]. In the course of time, hybrid and modified approaches have also been suggested by authors such as HGA [15], MPSO [16], adaptive DE [17] and HSA [18]. The most recent heuristic approaches to date are CSA [19] SOS [20], GSA-SQP [21], RTA [22], IIWO [23], WCA [24], GWO [25] and MVPA [26]. Many of these heuristic methods have been applied only to conventional distribution networks. Nevertheless, the more efficient heuristic approach to resolving microgrid protection coordination remains space for implementation.

The main contribution of this paper is to apply a nature-inspired novel evaporation rate water cycle algorithm (ERWCA) to the standard IEC microgrid benchmark. The main purpose of this article is to optimize the TDS to enhance the microgrid protection coordination, which leads to a reduction in operating time of all mounted OCRs in the microgrid. The IEC microgrid benchmark is built-in ETAP, results obtained from ERWCA are compared to those from the existing techniques and the improved relay settings are identified. The structure of the article is as follows. Section 2 describes the problem formulation. The working principle of ERWCA and its application on OCR coordination problem are discussed in sections 3 and 4, respectively. Mathematical models, graphical and statistical results and comparison to other techniques are explained in section 5. Section 6 concluded the paper.

2. Problem formulation of protection coordination

This segment shows the mathematical formulations of protection coordination. OCR coordination can be defined as a multi-constrained optimization problem.

2.1 *Relay characteristics*

Due to its ease of service, an Inverse Definite Minimum Time (IDMT) relay is the most favoured relay within the OCR network. IDMT relay has been used in this work, and the inverse relay feature can be represented in Eq. (1) according to IEC 60255 [7]:

$$T = \frac{\beta \times TDS}{(PSM)^{\alpha} - 1} \quad \text{where} \quad PSM = \frac{I_{fault\ current}}{Pickup\ current} \tag{1}$$

β and α are the standard inverse characteristic constants considered as 0.14 and 0.02, respectively [20]. *PSM* is the plug setting multiplier.

2.2 *Objective function of OCR coordination*

The OCR coordination issue aims to reduce the total operating time of the relay installed in the system by deciding the TDS as a parameter with the maintained constraints. We may describe the objective function as follows:

$$\text{minimize } z = \sum_{i=1}^{n} T_{ik} W_j \tag{2}$$

where z is the objective function of OCR coordination formulation, n represents the total installed relays and T_{ik} denotes the operating time of i^{th} relay at fault location k. W_j denotes the weighting factor. The distribution feeders are short in length and equally divided in length. Consequently, weights are also equal. Therefore, W_j is considered as 1 ($W_j = 1$) [24].

2.3 *Constraints*

The objective function given in Eq. (1) is subjected to the following constraints:

2.3a *TDS constraint*: In a well-coordinated scheme, TDS is the key factor to handle the coordination time. Therefore it can be stated as follows:

$$TDS_{i,min} \leq TDS_i \leq TDS_{i,max} \tag{3}$$

$TDS_{i,min}$ and $TDS_{i,max}$ shows the minimum and maximum value of *TDS*, respectively. Generalized values are $TDS_{i,min}$ = 0.025 and $TDS_{i,max} = 1.1$ [19].

2.3b *Relay operating time constraints*: Operating time may be applied as a limit for applying the minimum and maximum operating periods for each OCR. Therefore, the operating time variable can be expressed as

$$t_{i,min} \leq t_i \leq t_{i,max} \tag{4}$$

where $t_{i,min}$ and $t_{i,max}$ are the lower and upper limits on relay operating time, respectively.

The standard values for $t_{i,min}$ and $t_{i,max}$are 0.1 and 1.1 s, respectively [20]. This constraint suggests that the relay response will be faster to lower the relay operating time and thus lower the *TDS*; $t_{i,max}$ sometimes may differ according to the network configuration.

2.3c *PS constraints:* An appropriate PS also fastens the response to the relay. The constraints on PS are

$$PS_{i,min} \leq PS_i \leq PS_{i,max}. \tag{5}$$

$PS_{i,min}$ and $PS_{i,max}$ are the lower and upper values for PS, respectively.

2.3d *Coordination constraints:* Whenever a fault takes place, all primary and secondary relays in the network experience the fault and proceed to run concurrently. Although both relays simultaneously detect this fault, the primary relay will always act first in the ideal coordinate system and backup relays will work after a predefined time interval. Therefore, in order to avoid false tripping, an appropriate gap in coordination between the relays is needed under some time limits. The constraint on coordination can be mentioned as follows:

$$t_{b_j} - t_{p_i} \geq CTI \tag{6}$$

where t_{b_j} represents the functioning time of jth backup relay, t_{p_i} is the functioning time of ith primary relay and CTI is the coordination time interval. The CTI value could be considered to be within 0.2–0.5 s depending upon the CB speed [4]. In this paper, CTI is considered as 0.3 s.

3. ERWCA

ERWCA is a metaheuristic algorithm, inspired by nature and published in 2015, developed to optimize ongoing problems [27]. It is important to note that ERWCA is a revised form of the WCA that was adopted in 2012 [28]. WCA is encouraged by the process of water sequence: downstream movements of the river and streams towards the sea. ERWCA upgrades the old WCA by adding the evaporation situation that provides the benefit of a greater spread between the phases of exploitation and exploration compared with the WCA. It also increases the convergence rate into a global solution with positive performance relative to the WCA. In [29], the authors applied ERWCA to solve the efficient parameter estimate of the PV system and obtained promising results in contrast with the previously published research. Haroon and Malik [30] also used ERWCA in the environmental economic scheduling of hydrothermal energy systems problem and claimed superiority of ERWCA over the existing evolutionary algorithm. Relay coordination is a more constrained type of complicated optimization problem that cannot be solved directly by standard approaches. As a consequence, an inspiration evolved to use ERWCA for optimum relay coordination problems in the microgrid. The mathematical description of the ERWCA is discussed here.

3.1 *Initialization*

Initiate the population by random generation. N_p is the total number of stream population matrix generated as follows:

$$total\,population = \begin{bmatrix} sea \\ river1 \\ river2 \\ . \\ . \\ streamNsr+1 \\ streamNsr+2 \end{bmatrix}$$

$$= \begin{bmatrix} x_1^1 & x_{2......}^1 & x_{nvar}^1 \\ x_1^2 & x_{2.....}^2 & x_{nvar}^2 \\ . & . & . \\ . & . & . \\ . & . & . \\ & & . \\ x_1^{N_p} & x_{2.....}^{N_p} & x_{nvar}^{N_p} \end{bmatrix} \tag{7}$$

where x_{nvar} is number of variables and N_p is the population number. N_{sr} is a predefined parameter; it presents the addition of the number of rivers and sea given in Eq. (8). The number of few remaining rivers that may flow directly to the sea is given by Eq. (9).

$$N_{sr} = no.\,of\,rivers + 1(sea), \tag{8}$$

$$N_{stream} = N_p - N_{sr}. \tag{9}$$

Each stream fills the river, and the river fills the sea. There are some streams that alter their path and directly meet the sea. The number of streams added to sea and river may be determined by the following Eq. (10):

$$NS_n = round\left\{\left|\frac{cost_n}{\sum_{i=1}^{N_{sr}} Cost_n}\right| N_{stream}\right\} \quad where \quad n = 1, 2, 3, \ldots, N_{sr}. \tag{10}$$

The round operator is used to assign only a positive integer to the river and sea.

3.2 *Motion of streams to the sea or rivers*

Y, the distance between river and stream, can be written as

$$Y \in (0, Cd), C > 1 \tag{11}$$

where d denotes the spacing between stream and river. The value of C varies from 1 to 2. Preferably C>1 is fixed to force the stream to flow in a direction different from those of the rivers. Therefore, the new positions of streams, rivers and sea are given by the following equations:

$$Y_{stream}^{i+1} = Y_{stream}^{i} + rand \times c\left(Y_{river}^{i} - Y_{stream}^{i}\right) \tag{12}$$

$$Y_{stream}^{i+1} = Y_{stream}^{i} + rand \times c\left(Y_{sea}^{i} - Y_{stream}^{i}\right) \tag{13}$$

$$Y_{river}^{i+1} = Y_{river}^{i} + rand \times c\left(Y_{sea}^{i} - Y_{river}^{i}\right) \tag{14}$$

where $rand$ denotes a randomly distributed number in [0, 1]. Eqs. (12) and (13) show that the stream flows straight to the sea. If the cost function of the stream is found to be better than that of its equivalent river then both river and stream exchange their position with each other. Similarly, this process is carried out with the location of river and sea.

3.3 *Phase of evaporation and rainfall*

Seawater starts to vaporize through evaporation as the stream and river meet the sea. It is also important to test whether the evaporation cycle is carried out by streams or rivers. The following state is checked for this evaporation cycle:

$$E_v C_1 Y^i_{sea} - Y^i_{river} < d_{max} \quad \text{or } rand < 0.1,\ i = 1, 2, 3, \ldots, N_{sr} - 1 \tag{15}$$

where d_{max} value is close to zero. If this condition is valid, the raining cycle should begin.

$$Y^{new}_{stream} = lb + rand(ub - lb). \tag{16}$$

Similarly, the evaporation state is tested for the stream immediately connected to the sea. The evaporation state for the stream is as follows:

$$E_v C_2 Y^i_{sea} - Y^i_{stream} < d_{max}, \quad i = 1, 2, 3, \ldots, N_{sr} - 1. \tag{17}$$

If this condition satisfied, the raining cycle begins with the following equation:

$$Y^{new}_{stream} = Y_{sea} + \sqrt{\sigma} \times \ rand \ \ n(1, N). \tag{18}$$

The σ helps the algorithm to search the stream in the shortest province close to the sea. Therefore, σ is set to 0.1 and *randn*(1, *N*) is the standard Gaussian number.

For stream search closer to the sea, set d_{max} is linearly decreased by the following equation:

$$d^{i+1}_{max} = d^i_{max} = \frac{d^i_{max}}{Max.iter}. \tag{19}$$

The raining process explained here is the same as the mutation phase in GA.

Some small streams and flows that are not able to enter into the sea region will evaporate entirely after some time elapse. This is the evaporation rate concept added in the water cycle algorithm procedure to give the best global optimum. This evaporation rate is defined as follows:

$$\varepsilon = \left\{ \frac{\sum_{n=2}^{N_{sr}} N_{sn}}{N_{sr} - 1} \right\} rand. \tag{20}$$

This equation confirms that a lower ε value gives better cost function compared with a higher ε value. It denotes that the river that consists of more quantity of streams has lesser chances of evaporation as compared with the river having less number of streams. Therefore for better performance, the next evaporation condition is added for a few numbers of streams and rivers to perform the raining process again. This condition is as follows:

$$E_v C_3 \exp\left(\frac{-iterno.}{Max.Iter}\right) < \ rand \quad \text{and} \quad NS_i < \varepsilon.. \tag{21}$$

If Eq. (21) is satisfied then again the rain process begins using Eq. (16). If any river satisfies the evaporation condition, then that particular river with its stream is removed out and a new river and stream position is created.

4. Implementation of ERWCA for relay coordination problem

The following steps need to be followed for implementation of ERWCA algorithm on relay coordination problem [27]:

Stage 1. Create an initial population matrix for *TDS* by Eq. (7).
Stage 2. Assign the streams, rivers and sea.
Stage 3. Calculate the river flows and sea by Eq. (10).
Stage 4. The stream runs towards river and sea by Eqs. (12) and (13).
Stage 5. If the cost function of the stream has a reduced value with the associated river and sea, switch to Stages 6 and 7.
Stage 6. Swap the rivers/sea position with the stream.
Stage 7. Calculate river flow to the stream by Eq. (14).
Stage 8. If the cost function of the river has a reduced value with the associated sea, switch to Stages 9 and 10.
Stage 9. Swap the sea's position with the river.
Stage 10. Determine the rate of evaporation by Eq. (20).
Stage 11. When EvC_3 condition is satisfied, switch to Stage 12 or move to Stage 13.
Stage 12. Determine the current position of the river and stream by Eq. (16).
Stage 13. When EvC_1 and EvC_2 conditions are satisfied, switch to Stage 14 or Stage 15.
Stage 14. Again determine the current position of river and stream by Eqs. (16) and (17).
Stage 15. Decrease the *dmax* by Eq. (18).
Stage 16. Check the convergence criteria, else move to Stage 2.

5. Results and discussion

Fig. 1 indicates that the IEC microgrid consists of several synchronous DG modules. The simulation and design of the IEC microgrid were carried out in ETAP. The microgrid consists of a total of 11 wind turbines. Out of 11 wind turbines, 9 wind turbines are rated at 1.8 MW each and 2 wind turbines are rated at 7.65 MW each.

The OCR coordination framework was tested with the planned ERWCA to ensure the quality and efficiency of the test method. For this, 15 OCRs are scattered across the whole network. The CTR and PS for all 15 relays are shown in table 1. Three-phase symmetrical faults have been conducted in grid-connected mode at a different location. The initial power flow has been used to fix the

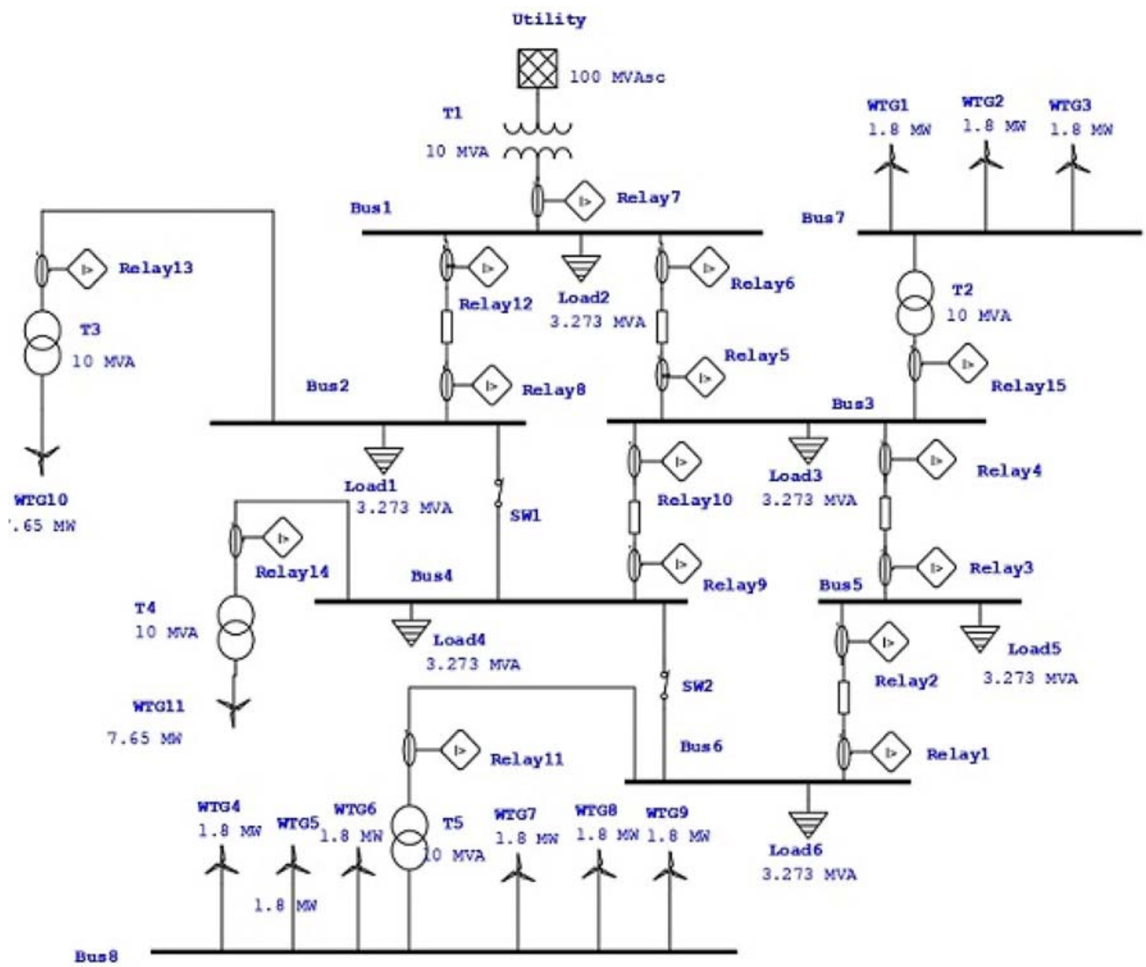

Figure 1. IEC standard microgrid benchmark.

CTR and PS of OCR. Furthermore, according to IEC 60909, short-circuit tests for three-phase symmetrical faults were done at various positions in grid-connected mode. The information for the present fault estimation at various positions is provided in Table 2. Details of the rating of all components are given in [31].

5.1 *ERWCA application*

In the present case, as said in Eq. (3), *TDS* limits are set at 0.025 and 1.1 (respectively, lower and upper bounds). According to Eq. (4), relay operating period constraints are set to 0.1 s. The *CTI* between the main relay and the backup relay is set to 0.3 s as shown in Eq. (6). The ERWCA code has been written in MATLAB. The suggested strategy has been tested for the IEC 60909 environment with a population size of 50 and an iteration of 100. The ERWCA algorithm code was tested 30 times and the minimum objective function value was recorded as 9.48 s. The optimized *TDS* of 15 relays and its overall operating time are shown in Table 3. (*TDS*1, *TDS*2, …, *TDS*15; the number reflects 15 OCR numbers). Table 3 also offers a summary of the proposed approach with existing techniques. Fig. 2 provides a comparison of the objective function with existing optimization strategy. The objective function graph of the proposed ERWCA is shown in figure 3.

Table 1. Relay's CTR and PS [3].

Relay	CT ratio	Plug setting
R_1	400:1	0.5
R_2	400:1	0.5
R_3	400:1	0.5
R_4	400:1	0.5
R_5	400:1	0.5
R_6	400:1	0.5
R_7	1200:1	1
R_8	400:1	0.5
R_9	400:1	0.5
R_{10}	400:1	0.5
R_{11}	400:1	0.65
R_{12}	400:1	0.5
R_{13}	400:1	0.88
R_{14}	400:1	0.65
R_{15}	400:1	0.55

Table 2. Different fault points, fault currents and primary backup relay pairs [3].

Fault points	Primary relay	Fault current (A)	Backup relay	Fault current (A)
F_1	R_2	4648	R_4	4648
	R_1	1648	R_{13}	1648
F_2	R_4	7260	R_6	5443
	R_4	7260	R_{15}	920
	R_3	1465	R_1	1465
F_3	R_6	9256	R_7	8375
	R_6	9256	R_8	923
	R_5	2635	R_{15}	737
F_4	R_{12}	5998	R_7	4572
	R_{12}	5998	R_5	1439
	R_8	991	R_{11}	991
F_5	R_{10}	4913	R_6	3416
	R_{10}	4913	R_{15}	578
	R_9	991	R_{14}	991

Table 3. Optimized TDS and total operating time.

TDS	PSO	WCA	ERWCA
TDS 1	0.1795	0.1741	0.1163
TDS 2	0.1371	0.1327	0.0465
TDS 3	0.0880	0.0870	0.0291
TDS 4	0.3659	0.2654	0.1860
TDS 5	0.1812	0.1729	0.0379
TDS 6	0.4996	0.3982	0.3176
TDS 7	0.4045	0.3396	0.2424
TDS 8	0.3173	0.2662	0.1027
TDS 9	0.1359	0.0697	0.0250
TDS 10	0.1420	0.1328	0.0474
TDS 11	0.3233	0.2802	0.1434
TDS 12	0.1430	0.1333	0.0851
TDS 13	0.2028	0.1944	0.1157
TDS 14	0.1725	0.1162	0.0790
TDS 15	0.2346	0.1866	01344
Z (s)	23.201	19.2	9.4854
Net time gain (s)	13.716	9.715	

5.2 *Comparison of the proposed ERWCA to PSO and WCA*

The suggested solution is effectively tested on the standard IEC microgrid benchmark. The outcomes obtained from the proposed solution are consistent with the most popular and effective PSO and water cycle algorithm. The minimal value with the proposed approach is just 9.48 s, which is the total operating time for all 15 for the existing relay.

The suggested protection scheme offered for the given case study provides a quicker protective operation. Table 3 indicates that ERWCA has outstripped all existing methods. ERWCA has the advantage of 13.716 and 9.715 s over PSO and WCA, respectively. This benefit demonstrates the ERWCA algorithm predominance over the current techniques. The best aspect of the proposed strategy is that only 100 iterations are required to converge towards the optimum solution, whereas PSO and WCA have double iterations [3]. Fewer iterations contribute to less time for optimization. Characteristics of the convergence are shown in Fig. 3, which indicates the smoothness of convergence to the optimum value without violating the constraints.

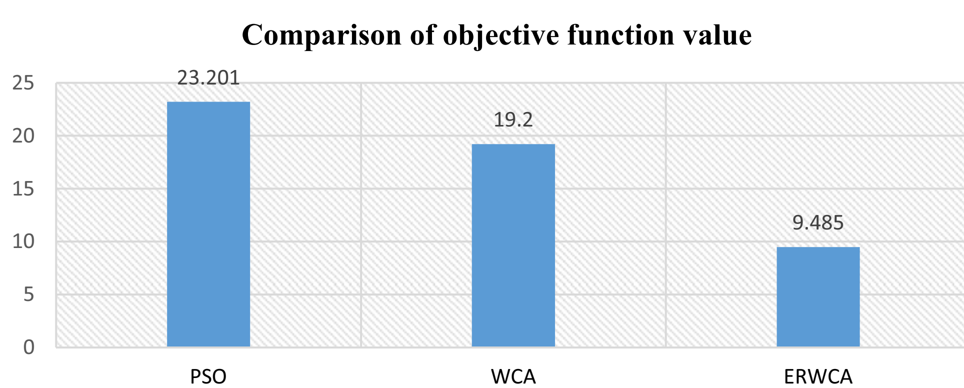

Figure 2. Comparison of objective function with different optimization techniques.

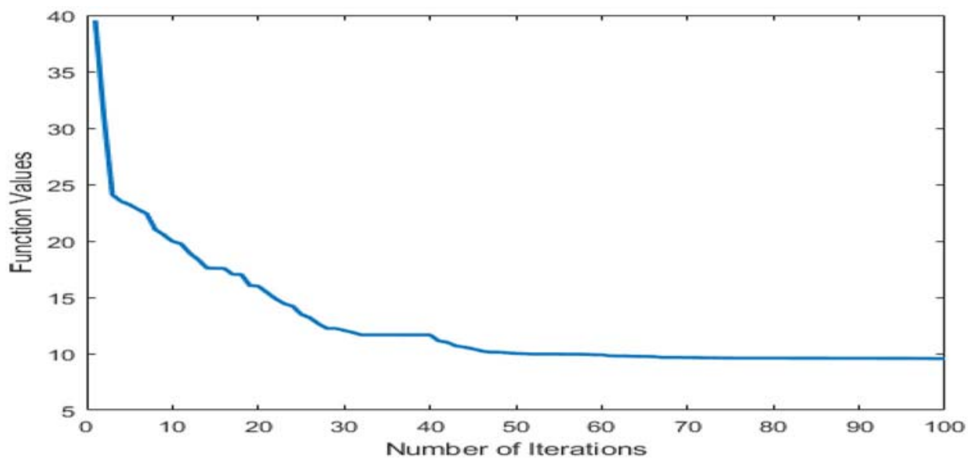

Figure 3. Convergence characteristic.

6. Conclusion

The IEC microgrid benchmark framework's protection coordination problem is mathematically formulated as a linear programming problem where the goal is to reduce the total relay action time in primary and backup operations. In this article, the ERWCA has been proposed for wind-turbine-based microgrid. ERWCA has reduced operating time by 13.716 and 9.715 s compared with PSO and WCA, respectively. It is revealed that the performance of the proposed ERWCA is outstanding over those of the particle swarm algorithm and water cycle algorithm. The findings show that the suggested method of coordinating protection with ERWCA offers the best optimal performance in less population and requires fewer iterations and reduced time compared with the existing algorithm. Besides, this reduced the overall running time for relays substantially, making it a reasonable option for microgrid systems.

References

[1] Hooshyar A and Iravani R 2017 Microgrid protection. *Proceedings of the IEEE* 105(7): 1332–1353

[2] Aghdam T S, Karegar H K and Zeineldin H H 2018 Optimal coordination of double-inverse overcurrent relays for stable operation of DGs. *IEEE Transactions on Industrial Informatics* 15(1): 183–192

[3] El Naily N, Saad S M, El Misslati M M and Mohamed F A 2019 Optimal protection coordination for IEC microgrid benchmark using water cycle algorithm. In: *Proceedings of the 10th International Renewable Energy Congress (IREC)*, pp. 1–6

[4] Gokhale S S and Kale V S 2016 An application of a tent map initiated Chaotic Firefly algorithm for optimal overcurrent relay coordination. *International Journal of Electrical Power & Energy Systems* 78: 336–342

[5] Chattopadhyay B, Sachdev M S and Sidhu T S 1996 An online relay coordination algorithm for adaptive protection using linear programming technique. *IEEE Transactions on Power Delivery* 11(1): 165–173

[6] Hussain M H, Rahim S R A and Musirin I. 2013 Optimal overcurrent relay coordination: a review. *Procedia Engineering* 53(1): 332–336

[7] Bedekar P P, Bhide S R and Kale V S 2010 Optimum coordination of overcurrent relay timing using simplex method. *Electric Power Components and Systems* 38(10): 1175–1193

[8] Noghabi A S, Mashhadi H R and Sadeh J 2010 Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming. *IEEE Transactions on Power Delivery* 25(3): 1348–1354

[9] Papaspiliotopoulos V A, Korres G N and Maratos N G 2017 A novel quadratically constrained quadratic programming method for optimal coordination of directional overcurrent relays. *IEEE Transactions on Power Delivery* 32(1): 3–10

[10] Birla D, Maheshwari R P and Gupta H O 2007 An approach to tackle the threat of sympathy trips in directional overcurrent relay coordination. *IEEE Transactions on Power Delivery* 22(2): 851–858

[11] Razavi F, Abyaneh H A, Al-Dabbagh M, Mohammadi R and Torkaman H 2008 A new comprehensive genetic algorithm method for optimal overcurrent relays coordination. *Electric Power Systems Research* 78(4): 713–720

[12] Asadi M R and Kouhsari S M 2009 Optimal overcurrent relays coordination using particle-swarm-optimization algorithm. In: *Proceedings of the 2009 IEEE/PES Power Systems Conference and Exposition*, pp. 1–7

[13] Shih M Y, Salazar C A C and Enríquez A C 2015 Adaptive directional overcurrent relay coordination using ant colony optimisation. *IET Generation, Transmission & Distribution* 9(14): 2040–2049

[14] Rodporn S, Kulworawanichpong T, Oonsivilai A, Uthitsunthorn D and Oonsivilai R 2012 Optimal coordination of overcurrent relays using differential evolution. In: *Proceedings of the 9th International Conference on Electrical Engineering/*

Electronics, Computer, Telecommunications and Information Technology, pp. 1–4

[15] Bedekar P P and Bhide S R 2010 Optimum coordination of directional overcurrent relays using the hybrid GA–NLP approach. *IEEE Transactions on Power Delivery* 26(1): 109–119

[16] Zeineldin H H, El-Saadany E F and Salama M M A 2006 Optimal coordination of overcurrent relays using a modified particle swarm optimization. *Electric Power Systems Research* 76(11): 988–995

[17] Moirangthem J, Krishnanand K R, Dash S S and Ramaswami R 2013 Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays. *IET Generation, Transmission & Distribution* 7(4): 329–336

[18] Barzegari M, Bathaee S M T and Alizadeh M 2010 Optimal coordination of directional overcurrent relays using harmony search algorithm. In: *Proceedings of the 9th International Conference on Environment and Electrical Engineering*, pp. 321–324

[19] Sarkar D, Kudkelwar S and Saha D 2019 Optimal coordination of overcurrent relay using crow search algorithm *Smart Science* 7(4): 282–297

[20] Saha D, Datta A and Das P 2016 Optimal coordination of directional overcurrent relays in power systems using symbiotic organism search optimization technique. *IET Generation, Transmission & Distribution* 10(11): 2681–2688

[21] Radosavljević J and Jevtić M 2016 Hybrid GSA–SQP algorithm for optimal coordination of directional overcurrent relays. *IET Generation, Transmission & Distribution* 10(8): 1928–1937

[22] Wadood A, Gholami Farkoush S, Khurshaid T, Kim C H, Yu J, Geem Z W and Rhee S B 2018 An optimized protection coordination scheme for the optimal coordination of overcurrent relays using a nature-inspired root tree algorithm. *Applied Sciences* 8(9): 1664

[23] Srinivas S T P 2019 Application of improved invasive weed optimization technique for optimally setting directional overcurrent relays in power systems. *Applied Soft Computing* 79: 1–13

[24] Kudkelwar S and Sarkar D 2019 Online implementation of time augmentation of over current relay coordination using water cycle algorithm. *SN Applied Sciences* 1(12): 1628

[25] Korashy A, Salah K, Abdel-Raheem Y and Francisco J 2018 Solving optimal coordination of direction overcurrent relays problem using grey wolf optimization (GWO) algorithm. In: *Proceedings of the 20th International Middle East Power Systems Conference (MEPCON)*, pp. 621–625

[26] Korashy A, Salah K, Abdel-Raheem Y and Francisco J 2019 Most valuable player algorithm for solving direction overcurrent relays coordination problem. In: *Proceedings of the 2019 International Conference on Innovative Trends in Computer Engineering (ITCE)*, pp. 466–471

[27] Sadollah A, Eskandar H, Bahreininejad A and Kim J H 2015 Water cycle algorithm with evaporation rate for solving constrained and unconstrained optimization problems. *Applied Soft Computing* 30: 58–71

[28] Eskandar H, Sadollah A, Bahreininejad A and Hamdi M 2012 Water cycle algorithm—a novel metaheuristic optimization method for solving constrained engineering optimization problems. *Computers & Structures* 110: 151–166

[29] Kler D, Sharma P, Banerjee A, Rana K P S and Kumar V 2017 PV cell and module efficient parameters estimation using Evaporation Rate based Water Cycle Algorithm. *Swarm and Evolutionary Computation* 35: 93–110

[30] Haroon S S and Malik T N 2016 Evaporation rate based water cycle algorithm for the environmental economic scheduling of hydrothermal energy systems *Journal of Renewable and Sustainable Energy* 8(4): 044501

[31] Kar S 2017 A comprehensive protection scheme for micro-grid using fuzzy rule base approach. *Energy Systems* 8(3): 449–464